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Liu, C.T., "Fracture Mechanics and Service Life Prediction Research".

AFOSR Program Review

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FRACTURE MECHANICS AND SERVICE LIFE PREDICTION RESEARCH

AFOSR TASK NUMBER 2302 BP

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Abstract

The main issues in service life prediction of solid rocket motors are the lack of a fundamental understanding of crack growth behavior under service loading conditions and a reliable methodology to predict crack growth. It is relatively unknown in the areas of microstructure effects on damage initiation and evolution, large deformation effect on crack growth, and the effects of mismatch of material properties of a bond system on the stress fields near the interfacial crack tip. This program consists of five major tasks: Task I - predicting the initial crack length in high stress regions; Task II - crack instability and growth models; Task III - numerical modeling of crack growth; and Task IV - interfacial fracture of bimaterial bond systems. The program's basic approach involves a blend of analytical and experimental studies. In general, mechanisms and mechanics involved in cohesive fracture in a solid propellant and adhesive fracture in bond systems are emphasized. Program results will provide a basis for developing advanced crack growth and service life prediction technologies for predicting the service life of solid rocket motors. The implementation of these advanced technologies will not only increase the reliability of the solid rocket motors but also significantly reduce the motor replacement costs.

Task I: Predicting the Initial Crack Length in High Stress Regions

The objective of this study is to develop a technique to predict the initial crack length in a high stress region. The developed technique will be used to predict the initial crack length in solid rocket motors.

In this task, a micro-macromechanical approach was developed to model and simulate crack initiation and propagation in a solid propellant. The approach was based on a simplified micromechanical model, damage mechanics at the micro-level, and finite element analysis at the macro-level. Both micromechanical and macromechanical analyses were conducted in tandem. The developed technique together with a phenomenological criterion were used to predict the initial crack length in the high stress region of specimens with a center hole. The specimens were subjected to different strain rates at room temperature. In FY99, a mechanistic criterion was developed and used to predict the initial crack length in high stress regions. The criterion was based on the instability of the damaged material just ahead of the crack tip. The initial crack length is equal to the length of unstable material zone when the damage at the crack tip element is saturated. Based on this criterion, the predicted crack length was 1.2 mm for the specimen with a 6.35-mm hole and 1.5 mm for the specimen with a 12.7-mm hole, respectively. Experimental results indicate that the specimen with the

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smaller hole showed initial crack lengths of 1.1 mm, 1.2 mm, and 1.3 mm while the specimen with the larger hole showed initial crack lengths of 0.9 mm, 0.96 mm, 1.57 mm, and 1.7 mm, respectively. Therefore, considering the nonhomogeneous nature of the material, the comparison is reasonably good.

Task II: Crack Instability and Growth Models

The objectives of this study are to (1) obtain a fundamental understanding of damage and deformation mechanisms at microscopic scales, (2) investigate the effect of microstructure on strain distributions, (3) determine fracture parameters based on a hybrid approach, and (4) develop short crack growth models.

In this study, the strain fields within a 2-mm region near the crack tip in a particulate composite containing hard particles embedded in a rubbery matrix were determined using a digital image correlation technique. The specimen was subjected to a constant strain rate loading condition at room temperature. During the test, digital images were obtained at a given time interval, and they were analyzed, using a digital image correlation program, to determine the strain fields near the crack tip. In addition a real-time x-ray technique was used to monitor damage initiation and evolution processes near the crack tip. Experimental findings reveal that the heterogeneity of the microstructure plays a key role in the local damage and strain distribution near the crack tip (Figure 1). Figure 1 shows that the strain fields are highly inhomogeneous and the high strain regions are localized in the neighborhood of the crack. The average size of these high strain regions is approximately 400 microns in diameter. Depending on the location of the high strain regions, voids may develop in the high strain regions, and the crack might grow by the coalescence of the voids with the crack tip. The crack-void interaction is a contributing factor to the fluctuation of crack growth behavior in this material. Experimental results also reveal that local strain rates are significantly higher than the applied strain rate and these high strain rate regions are localized within 1 mm of the crack tip. In the damage analysis, real-time x-ray data indicates that the damage zone size and the intensity of damage inside the damage zone increase with increasing time. The damage fields are roughly commensurate with the strain fields in the specimen. This suggests that the strain fields measured on the surface of the specimen may reasonably represent the through thickness effect in an average sense. Using the strains outside the localized high strain region near the crack tip, it is possible to calculate the J integral value using a continuum approach. Due to the inhomogeneous nature of the material, the calculated J integral values fluctuate along the path of integration. However, the averaged values of the J integral along different paths of integration are close to each other, and, on a first approximation, the averaged J integral value can be considered path independent. A comparison of the J integral values obtained both experimentally and numerically reveals a good correlation between them. In addition, crack growth rates are determined, and a crack growth model, relating the crack growth rate and the J integral, is developed.

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It is well known that for thick specimens made of metallic materials, the crack front will bow in the direction of the crack creating a thumbnail shape. This suggests that there is a plane strain constraint in the center portion of the specimen, which diminishes as one approaches

the side boundary. However, this may not be true for highly filled polymeric materials. Experimental data obtained from crack propagation tests on highly filled polymeric material specimen revealed that the crack front exhibited no "thumbnailing" both before and after growth. In other words, the crack front was ideally straight, but with local irregularities. This phenomenon is believed to be due to the development of damage at the crack tip. Experimental data show that the material at the tip of the crack suffers very large elongation and is nearly straight. The highly strained or damaged zones extend ahead of the crack tip, appearing as an equilateral triangle with the crack tip as its base. This damage zone is known as the failure process zone, which is a key parameter in viscoelastic fracture mechanics. When the local strain reaches a critical value, small voids are generated in the failure process zone. Consequently, there are a large number of strands, essentially made of binder material, which separate the voids that form inside the failure process zone. Under this condition, the transverse constraint is minimized. The development of the failure process zone together with the straight crack front suggest that, within the failure process zone, the transverse constraint is very small and that a plane strain fracture toughness does not exist for this material.

A plot of the critical mode I stress intensity factor K_{Ii} for the onset of crack growth as a function of the specimen thickness is shown in Fig 2. According to Fig 2, the variations of K_{Ii} among different specimen thicknesses are within experimental scatter. Therefore, as a first approximation, it can be assumed that K_{Ii} is independent of specimen thickness. In addition to the experimental study, a three-dimensional micro-macrodamage analysis was conducted to determine damage initiation and evolution processes in the specimen. The results reveal that the damage distribution is uniform along the crack front, resulting in a straight crack front. Also, the results of three-dimensional linear elastic numerical analyses reveal that crack tip damage induces a uniform distribution of K_I through the specimen thickness. These results support the straight crack front observed experimentally both before and after the crack growth.

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Task III: Numerical Modeling of Crack Growth Behavior

The objectives of this investigation are to (1) simulate crack growth in solid propellants as a function of loading rate and to compare to available experimental data; (ii) develop fracture initiation and growth criteria; and (iii) provide fundamental understanding of the links between damage and fracture mechanics.

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In FY99, a previously developed nonlinear time-independent constitutive model was refined to include the time dependence (viscoelasticity) in the model. The model was incorporated in a finite element computer code which can be used to investigate the effect of relaxation of the stress field both before and during crack growth. Currently, we are evaluating the accuracy of the developed model in predicting crack growth behavior in a solid propellant.

Task IV: Interfacial Fracture of Bimaterial Bond Systems

The objectives of this study are to determine the three-dimensional and residual stress effects on the distribution of the stress intensity factor (SIF) K , along the interfacial cracks in bimaterial specimens. In this task, both stress frozen and photoelastic techniques were used

to determine the SIF along the interfacial cracks in bimaterial specimens, using a three-specimen test method. In FY98, we had successfully measured stress intensity factors by this method for through cracks both near to and within bondlines between incompressible materials of different moduli. The present study involves ^N effort to extend the method developed for through cracks to measurement of stress intensity factors in part through cracks in bondlines between materials of different modulus. The objectives of the current study are to (1) determine the three-dimensional geometrical effect on the stress intensity factor distribution along the crack front of part through cracks and (2) the relative significance of such cracks when compared with through cracks. A three specimen test series was conducted for each crack depth involving (1) a homogeneous edge cracked specimen, (2) a homogeneous bonded edge cracked specimen, and (3) an edged cracked bimaterial specimen. After no load and fully loaded stress freezing cycles, slices were removed as indicated in Fig 3. The results revealed that there was little variation, within experimental scatter, between the side slices and the center slice, but center slice results were always higher so only center slice results are reported.

Finally, when comparing results of the part through cracks with those for through cracks by matching a/t for the part through crack with a/w of the through crack at 0.25, the through crack yielded higher SIF values in the ratio of $1.82/1.21 = 1.50$ suggesting that the part through cracks are much less severe (as expected).

Acknowledgment/Disclaimer

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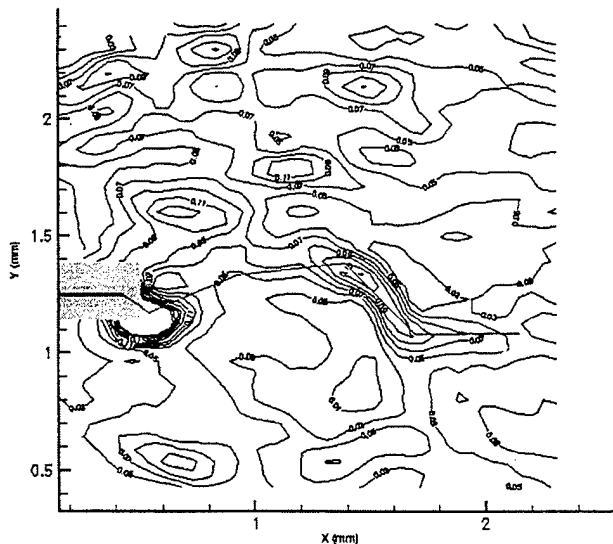
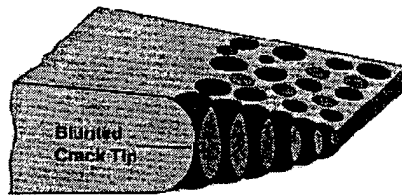
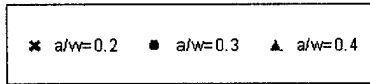
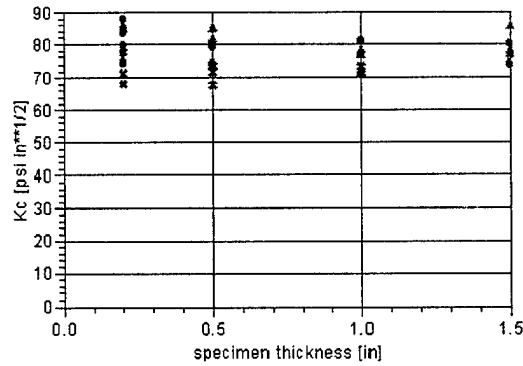


Figure 1 - Strain Contour Plot from Digital Image Correlation Experiments

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Highly Damaged Zone

Crack Tip Damage Model

Figure 2 - Fracture Initiation Toughness Variation with Thickness and Damage Zone Near Crack Tip

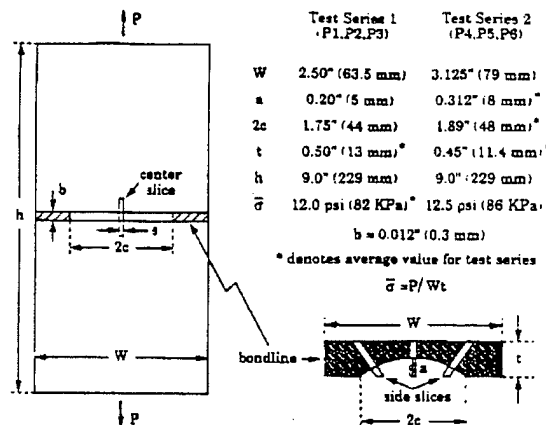


Figure 3 - Photoelastic Stress Freezing Specimen Geometry